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Bulk and fast ion diagnostic in the Large Helical Device using collective Thomson scattering

Understanding the behavior of bulk and fast ions is a major concern in fusion devices. A collective Thomson scattering (CTS) diagnostic is one of candidates to measure those charged particles and their fusion products especially in high energy region. In the Large Helical Device (LHD), a CTS diagnostic system has been developed utilizing a high-power 77-GHz gyrotron as a probing beam. A CTS diagnostic system has been developed to measure the velocity distribution function in JET, TEXTOR, and ASDEX-UG, and has been designed for ITER [1–3]. These systems use high-power gyrotrons with frequencies of 140, 110, 105, and 60 GHz and powers of a few hundred to ~1000 kW to generate a probing beam.

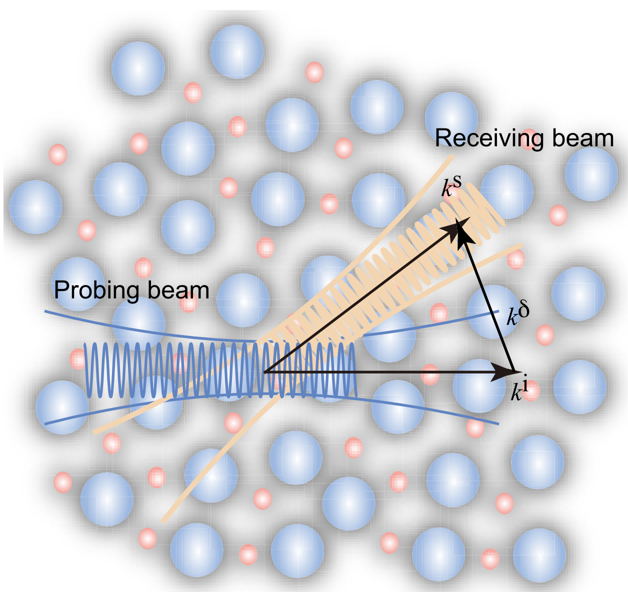

Fig. 1. Vector diagram of incident and scattered waves.

The fast ion velocity distribution and dynamics are obtained from the frequency spectrum of scattered radiation only when the collective condition, $1/k\lambda_D>1$, is satisfied, where λ_D is the Debye length, and the fluctuation vector $\boldsymbol{k}^\delta = \boldsymbol{k}^s - \boldsymbol{k}^i$ is given by the incident and scattered wave vectors, $\boldsymbol{k}^i$ and $\boldsymbol{k}^s$, respectively (see Fig. 1).

The scattered radiation is very weak, so it is essential to utilize a high-power coherent source. Gyrotrons with 60–a few hundred GHz satisfy the collective condition and are suitable for CTS diagnostics. The CTS diagnostic requires a sensitive receiver system to detect the scattered radiation from the plasma. In 2008 we designed the LHD CTS receiver system [4], and after that we installed it and obtained initial results for scattered spectra measured by the CTS diagnostic [5].

The scattered radiation is resolved into 8 channels at the receiver system. For more accurate velocity distribution function measurements, the number of channels is increased from 8 to 32 channels. These results have already been reported in Refs. [6, 7]. Figure 2 shows a broadband heterodyne receiver system, which mainly consists of a notch filter, a mixer with a local oscillator, some low-noise RF amplifiers, a filter bank, diodes, and video amplifiers, which are connected to the data acquisition

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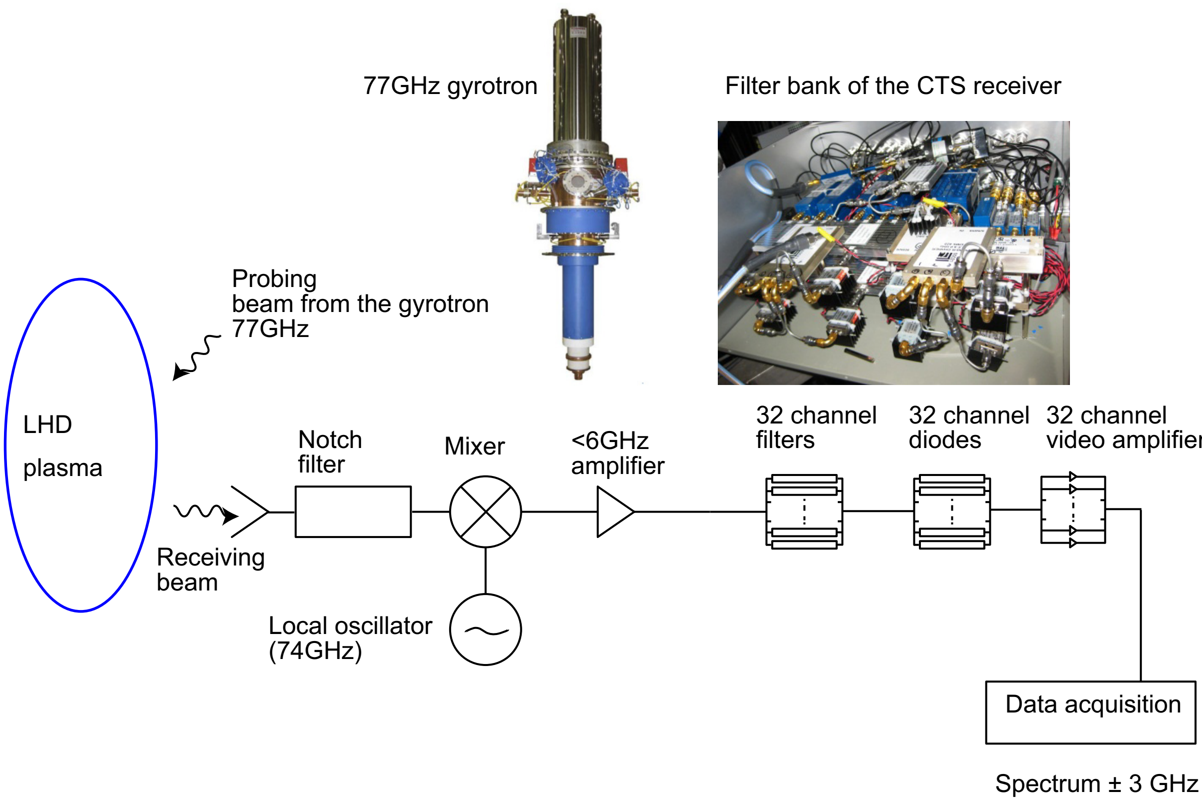

Fig. 2. The CTS diagnostic system with a megawatt gyrotron probing beam and the CTS broadband receiver system for the detection of scattered radiation.

system. The scattered radiation is reconstructed to obtain the ion velocity distribution. The 32 channels were calibrated using measurements of liquid nitrogen radiation or electron cyclotron emission (ECE) during plasma discharges. An amplitude-modulated probing beam with a frequency of 50 Hz is injected into the plasma for the subtraction of the background ECE. The probing and receiving beams are controlled by the final steering mirrors (Fig. 3). The scattered radiation from the overlap between the probing and the receiving beams is transmitted to the front end of the CTS receiver system by the waveguides for electron cyclotron heating (ECH).

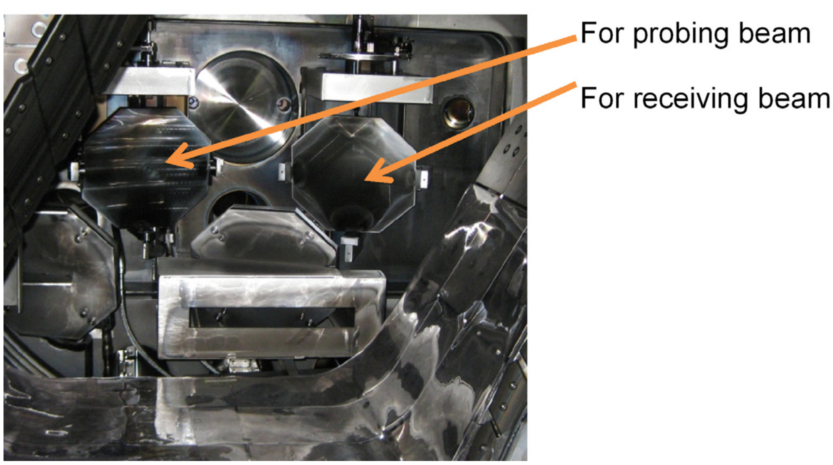

Fig. 3. Final steering mirrors inside the LHD vacuum vessel for probing and receiving beams.

The time evolution of the measured CTS spectrum is shown in Fig. 4. The plasma is sustained by two auxiliary neutral beams: a perpendicular (NB4) and a parallel (NB3) beam. The $\boldsymbol{k}^{\delta}$ vector, where the beam overlap exists, is nearly perpendicular to the magnetic field. Therefore, the intensity of the CTS spectrum in this case is considered to be sensitive to the perpendicular NB4 beam. From the above viewpoint, NB4 is injected, followed by an increase of intensity and frequency spread (proportional to particle velocity), as shown by the arrows in Fig. 4.

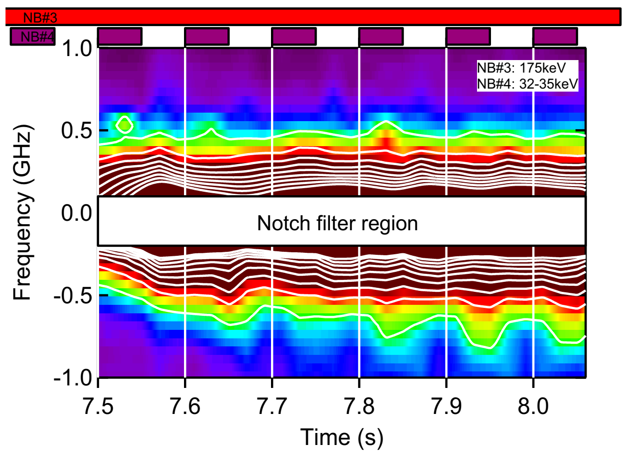

Fig. 4. Spectrogram of scattered radiation as measured by the CTS diagnostic in LHD shot 101719. The frequency is proportional to the velocity ($v \propto \omega / k^{\delta}$). The 1-GHz frequency shift corresponds to the energy of the40-keV NB4.

We have started comparison of both experiment and simulation to understand both the CTS spectrum and the use of predictive simulation for fast ion confinement. Figure 5 is an example, which is calculated by an orbit-following Monte Carlo code (MORH) [8]. The fast-ion velocity-space distribution is calculated when one perpendicular and two parallel beams are injected. As the observation direction is at an angle of 100 degrees (the $\boldsymbol{k}^{\delta}$ vector in the figure), all particles are projected onto the $\boldsymbol{k}^{\delta}$ vector. After the treatment of this geometrical effect, we can obtain the one-dimensional velocity distribution in the bottom graph of Fig. 5. The next step is the development of a scattering spectrum analysis code that can handle any kind of velocity distribution, to compare with simulated and experimental results.

Work is in progress to improve the signal to noise ratio for the CTS receiver, high-purity probing beam, and fast scanning mirror system in preparation for the forthcoming LHD experimental campaign in summer 2012.

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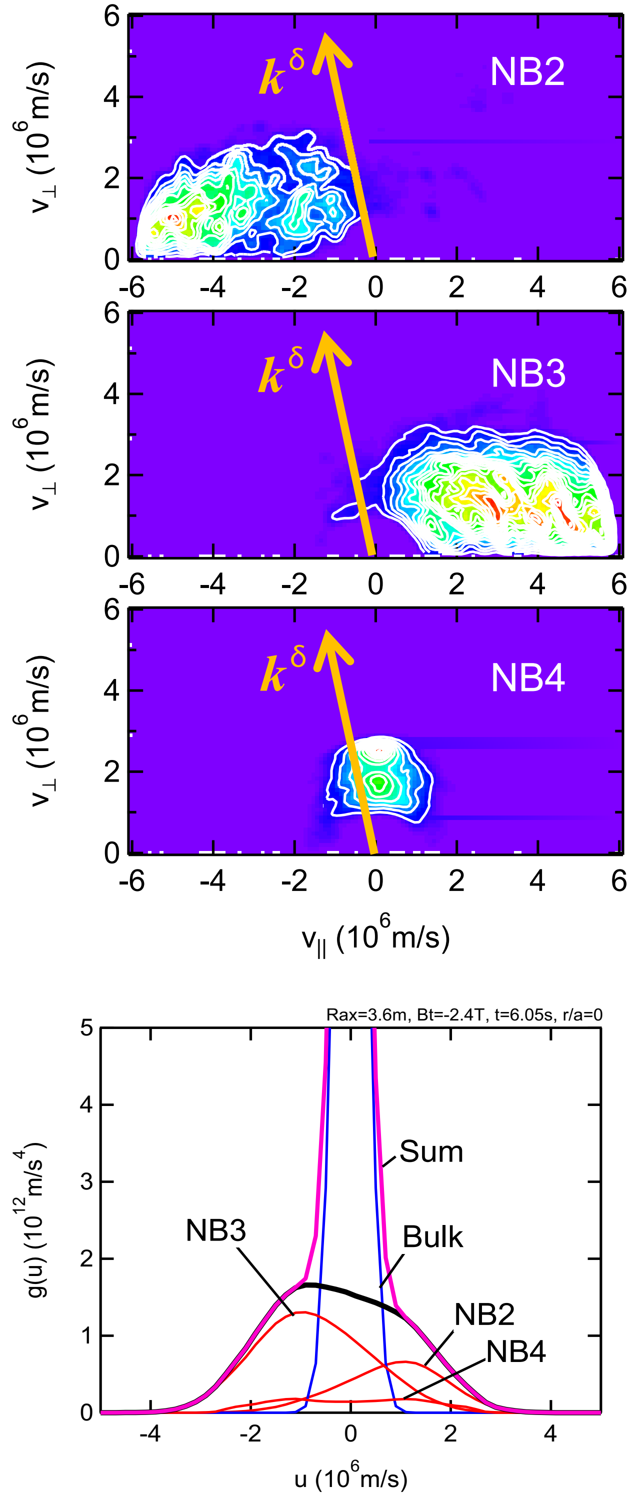

1D velocity distribution function (simulated)

Fig. 5. Top: Simulation of fast ion distribution during NB2, NB3, and NB4 injection using the MORH code. Bottom: 1D velocity distribution calculated from the simulated velocity-space distribution with a $\boldsymbol{k}^{\delta}$ vector of 100 degrees.

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Coordinated Working Group Meeting (CWGM9) for Stellarator-Heliotron Research

The 9th Coordinated Working Group Meeting (CWGM9) was held on 28 January 2012 at Australian National University, Canberra Australia, with15 experts participating. The meeting was composed of six sessions including the Opening, which discussed the evolution of CWGM and its central role for international collaboration in the International Energy Agency (IEA) Implementing Agreement for Cooperation in Development of the Stellarator-Heliotron (S-H) Concept (http://iea-shc.nifs.ac.jp/). The list of joint papers originated from CWGM was introduced to stimulate more joint activities to systematize the physics understandings in S-H plasmas. The achievements of CWGM8 (*Stellarator News*, Issue 131, April 2011, http://www.ornl.gov/sci/fed/stelnews/issue131.pdf) were also briefly mentioned.

Following the Opening, in the Energetic Particles session, D. A. Spong (ORNL) reported on a new code benchmark study of linear growth rates of energetic particle driven Alfvén eigenmodes (AE modes) in S-H plasmas. Currently, five different models (MEGA-R, AE3D-K, local analytic, CAS3D-K, and CKA-EUTERPE) are participating in the benchmark, and two toroidal AE (TAE) modes that were observed in LHD were selected for analysis. At this stage areas of both similarity and difference have been found among the codes, depending on how the particle weights are evolved and which of the two modes is examined. As the study progresses, it is expected to sort out the differences and to be extended to observations from other devices. It was also pointed out that for ITER, the impact of a large alpha particle population on AE modes is an important issue, and contributions from the S-H community are anticipated for discussions in the ITPA.

F. Castejon (CIEMAT) discussed the dynamics of fast ions coming from neutral beam injection (NBI) heating in three-dimensional (3D) systems using Monte Carlo codes, without any assumptions on the diffusive nature of transport, on the size of orbits, or on the conservation of kinetic energy. The codes FAFNER2 and HFREYA are linked to ISDEP (Integrator of Stochastic Differential Equations for Plasmas) in order to study such dynamics in TJ-II and LHD plasmas. The steady-state distribution function is obtained at several radial positions and from it, several interesting quantities, such as poloidal and toroidal rotation velocities, can be estimated. It has been found that the CNPA (Compact Neutral Particle Analyzer) spectra in TJ-II are in good agreement with the simulations. The slowing-down time is obtained by NBI blip experiments and simulations for TJ-II and LHD, with good agreement in both devices, showing also a good similarity with the Spitzer slowing-down formula in LHD and a strong difference in TJ-II, attributed to the larger radial extent of ion orbits.

The importance of the validation of numerical codes against experimental results and the resulting increased accuracy of predictions for energetic particle issues (especially for ITER) were pointed out.

A new Equilibrium in Experiment session was launched at CWGM9, reflecting increased interest in and activities on equilibrium reconstruction based on the progress of profile measurement, numerical code applications for experimental analysis, and the extension of the International Stellarator-Heliotron Profile Database (ISH-PDB), to increase its usability and scope. J. Geiger (Max-Planck, Greifswald) used function parameterization to try to shortcut the process for the interpretation of experiments (equilibrium reconstruction) by utilizing pre-calculated VMEC equilibria. In practice, reconstruction of flux surface shape is represented by Fourier components, R_{mn} and Z_{mn}, and then quantities such as r_{eff} (radial coordinate), coil currents, plasma current and plasma pressure, etc., can be represented using them, in W7-AS. This approach has been implemented for W7-X as a Web service. It will be utilized for mapping of diagnostics and simulations of diagnostic measurements.

C.Suzuki (NIFS) applied real-time magnetic coordinate mapping (so-called TSMAP) in LHD, which is based on searching for the "best-fit" coordinate mapping from a wide range of precalculated VMEC equilibria to make the measured electron temperature (by Thomson scattering) symmetric.

The progress of ion temperature (T_{i}) measurement by XICS (X-ray Imaging Crystal Spectrometer) in LHD and related equilibrium reconstruction research was reported by N. A. Pablant (PPPL). This diagnostic allows T_{i} measurements to be made under plasma conditions where existing diagnostics (e.g., CXRS) cannot be operated. The system is now fully commissioned and can provide line-integrated measurements of T_{i} and T_{e}. Local profiles of T_{i} and T_{e} are found through Doppler tomography utilizing the known plasma equilibrium. Initial comparisons against Thomson and CXRS show good agreement, demonstrating the applicability of this technique to helical geometries. There was discussion on how this diagnostic could be integrated into transport codes to provide T_{i} profiles to study heat transport in LHD. N. A. Pablant also presented a report on the S-H equilibrium reconstruction activity being conducted at PPPL.

The STELLOPT code, has been developed for S-H equilibrium reconstruction. It optimizes the VMEC input parameters to obtain a best match to diagnostic data using a modified Levenberg-Marquardt algorithm. Reconstructions were shown for several LHD discharges where optimization was done to match the following parameters: coil currents, stored energy, net toroidal current, and electron pressure. Work is in progress to add pitch angle measurements from the motional Stark effect diagnostic. Current development of STELLOPT is aimed at improving performance and user interaction to facilitate its routine use. The codes PIES and SPEC were introduced; they allow investigation of equilibria in the absence of good flux surfaces and complement work done using HINT2. Discussion addressed the integration of STELLOPT results into diagnostic interpretation and transport studies. It was proposed that comparisons of STELLOPT equilibria with those determined though functional parameterization and VMEC database approaches, as presented in this session, could be used to examine the accuracy of these fast lookup techniques.

The progress of the equilibrium registration attached to the registered experimental profiles in the ISH-PDB was reported by M.Yokoyama (NIFS), who presented as an example the examination of an LHD high-T_{i} discharge. The TSMAP-defined VMEC equilibrium (re-calculated by inputting parameters corresponding to the "best fit") was registered as a test case. The process for utilizing the equilibrium was also explained. Those interested in analyzing a registered discharge using their numerical codes can start the calculations either from a registered VMEC input or from the output files. This should speed up the transition of ISH-PDB from the "storage" phase to the "utilization" phase.

It was noticed that various approaches for equilibrium reconstruction/specification have been in progress (there was also a session in the following 18th International Stellarator-Heliotron Workshop), and it was pointed out that comparisons on these approaches would be beneficial to increase their validity and accuracy.

In the Transport Analysis session, M.Yokoyama (NIFS) presented an analysis of steady-state power balance in LHD, using TR-SNAP. This code has now been linked to TSMAP by establishing the interface to describe measured temperature and density profiles as a function of r_{eff} and to acquire NBI energy/port-through power. This suite was demonstrated and is now available to collaborators. It can replace the TSMAP-defined equilibrium by equilibria constructed in different ways, as discussed in the Equilibrium in Experiment session. This will provide an opportunity to test the impact of equilibrium properties on steady-state power balance analysis in an easy way.

A. Wakasa (Kyoto U.) reported on the status of the TASK3D development for the predictive simulation of reachable temperatures (and the resulting profiles) in LHD including turbulent transport modeling in addition to the established neoclassical diffusion coefficient database, DGN/LHD. It was pointed out that validation experiments in LHD should increase the accuracy of the prediction, and that a comparative study on a module-to-module basis, with, for example, the predictive transport code developed at IPP, would be valuable.

Rotation and momentum transport issues have gathered a lot of attention recently. In the Rotation session, recent activity at TJ-II was presented by J. A. Alonso (CIEMAT). Mass flows in (nonsymmetric) S-H plasma are expected to be dictated by NC ambipolarity and the parallel force balance equation. These devices are, therefore, best suited for testing neoclassical predictions on flow damping. External biasing provides a controlled perpendicular force that is easy to quantify. TJ-II has recently pursued different experimental approaches to test the pre-eminent role of neoclassical mechanisms in flow pattern regulation. At CWGM9, there was only one presentation on this topic. However, similar studies have been or are being performed in other devices, and thus a coordinated action seems appropriate, which could also help to expand our understanding of flows in symmetric configurations. J. A. Alonso has visited Heliotron J and LHD in March 2012, and moved to launch such a coordinated action.

We also had a session on Pellet Fueling. G. Motojima (NIFS) is starting to deal with fueling issues in a S-H power plant. The significance of pellet injection as the main fueling in S-H plasmas was discussed. Capability for higher-density plasma confinement in S-Hs provides an attractive scenario for a power plant. The key to make this realized is a reliable pellet injection system, such as the one operating on LHD. Research on pellet fueling was introduced. The conceptual design for Heliotron J was also presented. The pellet injection system for TJ-II, constructed with U.S. collaboration, is now nearly finished. Such installations will certainly enhance the collaborative research among several devices on physics and technological issues related to pellet injection and facilitate future collaborative development.

Opportunities for collaborative research on H-1NF were discussed by D. Pretty (ANU). In order to facilitate H-1NF data access for collaborators, a new data access system (H1DS) has been developed to provide a data interface that is simple and intuitive for new users and collaborators. The H1DS design utilizes the hypertext transfer protocol (HTTP) to provide an extensible web-service based application programming interface (API), which can interface with standard data analysis languages (Python, IDL, Matlab, Labview, etc.). A web-based MDSplus data viewer is now online at http://h1ds.anu.edu.au/mdsplus, providing simple navigation and basic processing of data. The new data system also includes a summary database, configurations database, and centralized documentation. A point of discussion was the possibility of deploying the H1DS software with datasets from other (non-MDSplus) S-H devices. Currently the Web service only supports MDSplus, but it is not very tightly coupled to it, so it would not take too long to implement on other systems (~ few weeks development time).

Progress towards an MHD Documentation Database (MDDB), occasionally discussed at previous CWGMs, was also introduced. This project aims to provide a reference documentation database of MHD modes using data mining techniques. Fluctuations are found by scanning Mirnov signals and "fingerprinting" coherent fluctuations by the phase difference between adjacent Mirnov channels; clustering algorithms are then used for unsupervised identification of the same fluctuation across many shots. These techniques have been used to identify Alfvén eigenmodes and other modes in H-1, TJ-II, and Heliotron J for thousands of shots. In order to generate the MDDB database, processing has started on a larger dataset, with ~50,000 shots and including LHD and W7AS; improved clustering algorithms capable of scaling to more than 100 data points are being explored. The discussion focused on what properties of fluctuations should be recorded when scanning Mirnov signals: for example, frequency spectral width may reveal growth rates.

Finally, it was pointed out that, in addition to widening the range of topics (the extent of the mountain), "flagship" topics (a peak of the mountain) should be intensively dealt with, so that CWGM becomes more visible and relevant in world-wide fusion research, through more outreach activities. Strategic discussions on how to make CWGM evolve will be continuously made in preparation for the next (10th) CWGM. The 10th CWGM, now being planned, is to be held 6–8 June 2012, in Greifswald, Germany. Your interest and participation are anticipated. The CWGM10 Web site is at
http://www.ipp.mpg.de/~dinklage/CWGM10/.

The materials presented at the 9th CWGM are available at http://ishcdb.nifs.ac.jp/cwgm9.html.

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M. Yokoyama (NIFS), on behalf of all of the participants in CWGM9.
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